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Relations Between Blue Whiting Biomass and Satellite Derived Phytoplankton and Temperature in the Norwegian Sea

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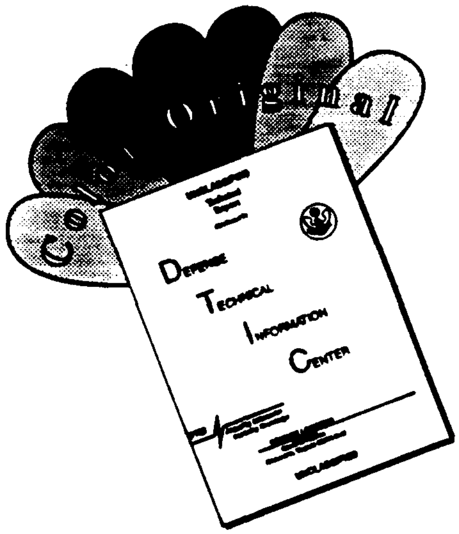

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Abstract

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Relations Between Blue Whiting Biomass and Satellite Derived Blue Phytoplankton and Temperature in the Norwegian Sea

I. Introduction

The distribution of fish populations in the world oceans is difficult to predict because of changing environmental conditions and our lack of understanding how fish respond to the ocean environment. Satellite oceanography provides a unique insight into understanding and knowledge of the ocean environment based on rapid synoptic mapping of the changing ocean surface environment. Attempts to use environmental surveillance techniques to predict the location of fish populations (Petterson et al., 1989; Montgomery et al., 1986) are most successful when the coupling between fish and remotely sensed parameters such as temperature or phytoplankton are strong (Laurs et al., 1984; Leming and Herron, 1986). The best example of these reconnaissance techniques occur when fish are highly correlated with one ocean parameter. As the fish distribution becomes coupled to broader multiocean parameters, our understanding of the correlations of distribution and ocean properties becomes more diffuse and harder to predict. This is especially evident for fish that feed in the food chain where complex interactions of physical and biological oceanographic processes are certain to impact the fish distribution. In these instances the applications of remote sensing to predict the occurrence of these fish distribution will certainly be more difficult to determine.

Fish behavior at higher levels in the food web is more difficult to understand since fish behavior responds to complex interactions of physical and biological processes. Rudimentary coupling of fish distribution and surface temperature for example are too simplistic and additional ocean properties are needed to predict behavior. Pelagic fish behavior are responsive to the interaction of physical ocean properties such as mixed-layer depth, temperature, density structure, wind mixing, frontal locations, solar insolation, etc., in addition to biological processes such as food resources, predations, chlorophyll profiles etc.

Pelagic fish with swim bladders can have a significant impact on the performance of low-frequency active acoustic systems (Love, 1990). Swim bladders can be strong reflectors of acoustic energy and account for high amounts of volume reverberation levels in the ocean. Active acoustic models used to predict and improve the Navy system performance have included inputs of the distribution and concentration of pelagic fish. These acoustic models can provide an approximation of the volume reverberation that can be expected within a given area from distributions of the fish size, numbers, and depth. Presently a major problem is estimating fish distributions; i.e., where and when are fish located. Present fish monitoring programs are severely limited and efforts are required to improve the technology. Limited information on total fish catch, location and species recruitment and overgrazing can be obtained through international fisheries organizations, such as the Food Agricultural Organization (FAO) of the United Nations and the International Council for the Exploration of the Sea (ICES). Fisheries data indicate that the distribution of most fish is difficult to predict at useful scales of resolution for naval tactical oceanography. This arises because the complexity of fish behavior and our lack of understanding of this behavior. At best we can attempt to perform simple correlation of fish populations with physical and biological properties occurring within the ocean.

This effort is an attempt to correlate remotely sensed ocean parameters with fish catch distributions. Specifically, we examine the coupling of surface phytoplankton and sea surface temperature (SST) data with survey estimates of blue whiting, in the Norwegian Sea during August from 1982 to 1986. This particular correlation was selected because excellent blue whiting distributional information and adequate satellite data were available. Additionally, the Norwegian Sea is an important area were high levels of low-frequency volume reverberation are known to occur and has significant importance for Naval tactical oceanography. A motivation for this study was that dense aggregation of blue whiting can be associated with high concentrations of chlorophyll and/or temperature distributions observed at the ocean surface.

Fisheries investigations have found that during summer, blue whiting feed heavily on euphausids and copepods (Anon, 1984) both of which feed on phytoplankton. Because of this relatively short food chain, blue whiting were found in regions of high zooplankton concentration along the warm side of the Iceland-Faroe front (Anon, 1984). The vertical migration of euphausids could provide the trophic link between near-surface phytoplankton and deep layers of blue whiting.

II. Satellite Data

A. Coastal Zone Color Scanner (CZCS)

CZCS, which operated from 1978 to 1986, provides accurate measurements of the ocean color (spectral water leaving radiance at 443, 520, and 550 nm) of the near surface. These satellite data can be used to estimate the intergrated phytoplankton distribution or the chlorophyll pigment concentration of the first attenuation length. Satellite algorithms have been developed that remove the atmospheric contamination that represents approximately 80-90% of the satellite signal to retrieve the water leaving radiance at the visible channels of CZCS (Gordon, 1978; Gordon and Clark, 1980a,b). The ratio of these channels have been shown to be strongly correlated with the phytoplankton concentration occurring in the upper ocean (Gordon and Clark, 1980a). CZCS had a ground resolution of approximately 1 km and repeat time of approximately four times a week. These satellite imagery clearly shows the spatial and temporal variability of the phytoplankton distribution. Phytoplankton concentrations have been shown to be associated with different physical water masses such as the Gulf Stream, shelf and slope waters, and cold and warm core rings (Gordon et al., 1983). Elevated phytoplankton concentrations are shown to be coupled with upwelling processes and wind events.

Mitchell et al. (1991) has identified problems in using universal remote sensing algorithms for predicting chlorophyll in high latitudes. Regional chlorophyll algorithms are suggested as a solution; however, these regional algorithms have not been developed. Although these problems are recognized, in this study we have used the conventional universal chlorophyll algorithms. Additionally, the satellite surface derived chlorophyll is substantially different from the integrated chlorophyll profile in ocean waters (Sathyendranath and Platt, 1989). Techniques to estimate total integrated chlorophyll would be more characteristic for this comparative study, however because of uncertainty in these techniques, we have elected to use only the surface derived chlorophyll concentration. Follow-on efforts will be focused on estimating a vertical profile of the chlorophyll distribution from the satellite data.

Average CZCS phytoplankton concentrations have been compiled for the world's oceans at a reduced 20-km^2 resolution and averaged over a 1-month period (Feldman et al., 1989). In this National Aeronautics and Space Administration (NASA) study, daily scenes of CZCS 1-km imagery were averaged spatially over the 20-km cell and temporally over monthly time periods to establish the mean phytoplankton concentration and standard deviation at that location. (Note that the monthly composite used only cloud-free pixels of CZCS data. The clouds, land, and low radiance pixel values are screened prior to compositing. Thus, the composite intergrates patches of cloud-free areas which, when averaged over a monthly period produce a cloud-free phytoplankton image). The monthly phytoplankton climatology has been created for the 92-month life of the CZCS satellite (November 1978 - June 1986).

The phytoplankton data base was assembled by the Naval Research Laboratory's (NRL) Ocean Color Laboratory using the PC-SeaPak image processing system (Firestone et al., 1989, McClain et al., 1990; Arnone and Oriol, 1992a). NRL's data base is organized into monthly averages representing 8 regions covering the globe. The techniques in the data organization and data formats and methods for statistically processing the techniques have been developed to address this data set. Specifically, the data base contains:

1. mean and standard deviation 20-km phytoplankton concentration.
2. the number of scenes (dates) were used for making each 20-km statistic.
3. the number of valid pixels used in making the 20-km statistics.

B. NOAA - Advanced Very High Resolution Radiometer AVHRR

The NOAA Series - AVHRR satellite data were used to determine the global SST field. The AVHRR satellite has a ground resolution of 1 km and a repeat time of twice a day. Thermal infrared (IR) channels were used to determine the "skin" SST. A multichannel sea surface temperature (MCSST) was used (McClain et al., 1982) to determine surface temperature to an accuracy of 0.6° C.

The SST monthly and weekly averages have been assembled into a data base by NRL in a similar method described above. The data was averaged spatially into 20-km^2 pixels and averaged temporally over a weekly period starting in 1981. SST compositing was assembled into a NASA Ocean Data System (NODS) product as a joint effort with the University of Rhode Island, the University of Miami and the NASA Jet Propulsion

Laboratory. NRL compiled a weekly data base of the SSTs for the identical regions as the phytoplankton distribution (Arnone and Oriol, 1991b). The weekly SST were assembled into monthly averages that were coincident in time and space with the phytoplankton data. All processing was performed using the PC-SeaPak image processing system.

III. Fish Migration and Phytoplankton Distribution

Acoustic surveys of blue whiting off the Norwegian coast are reported by Love (1990). Figure 1 illustrates the general migration pattern of blue whiting through the seasons. During the spawning season (March, April, and May) the fish are off the British coast. In June they migrate north into the Iceland-Faroe Ridge area. Later in summer (July) they begin to spread and encompass much of the Norwegian Sea region to feed. The feeding season extends though December. In January, they migrate southward across the Iceland-Faroe Ridge.

The monthly climatology of phytoplankton for the 6 years of CZCS data was compiled into the blue-whiting history described above. This sequence of phytoplankton imagery represents a general history of the phytoplankton patterns for 6 years and how it is correlated with the migration history of blue whiting in the North Atlantic. The mean phytoplankton distribution representing the spawning period (March, April, and May) is illustrated in figure 2. During spawning, blue whiting are typically in layers that are 20 to 100 m thick at depths of about 200-500 m. Notice the high phytoplankton concentrations along the coastal regions of Great Britain and Norway. The northern migration period (June) is illustrated in figure 3. Concentrations of adults are located in the Faroe-Shetland Channel and its southwestern approaches and to the southwest and west of the Faroes. The feeding period (July through November) is illustrated in figure 4. The post spawners' movement into the Norwegian Sea is controlled primarily by the extent of the east Icelandic Current. The extent of the cold-water front produced by this current with the warmer Norwegian Current has a dominant control on the distribution of blue whiting. The frontal positions are believed to have a strong control on the fish distribution. During the feeding period the blue whiting disperse widely, their actual distribution varying throughout the summer and from year to year. During the winter migration the solar angle was too low in the horizon to permit collection of ocean color data; hence, phytoplankton imagery is not available. The available phytoplankton distributions represent only the surface distribution to a depth of approximately one attenuation length (Gordon and McCluney, 1975). In most instances the elevated chlorophyll concentrations that typically occur at the mixed-layer depth (chlorophyll maximum) are not observed by the CZCS imagery. This represents a serious limitation of these data in that copepods and euphausids on which blue whiting feed will be located deeper within the water column, below the satellite derived measurements of surface chlorophyll.

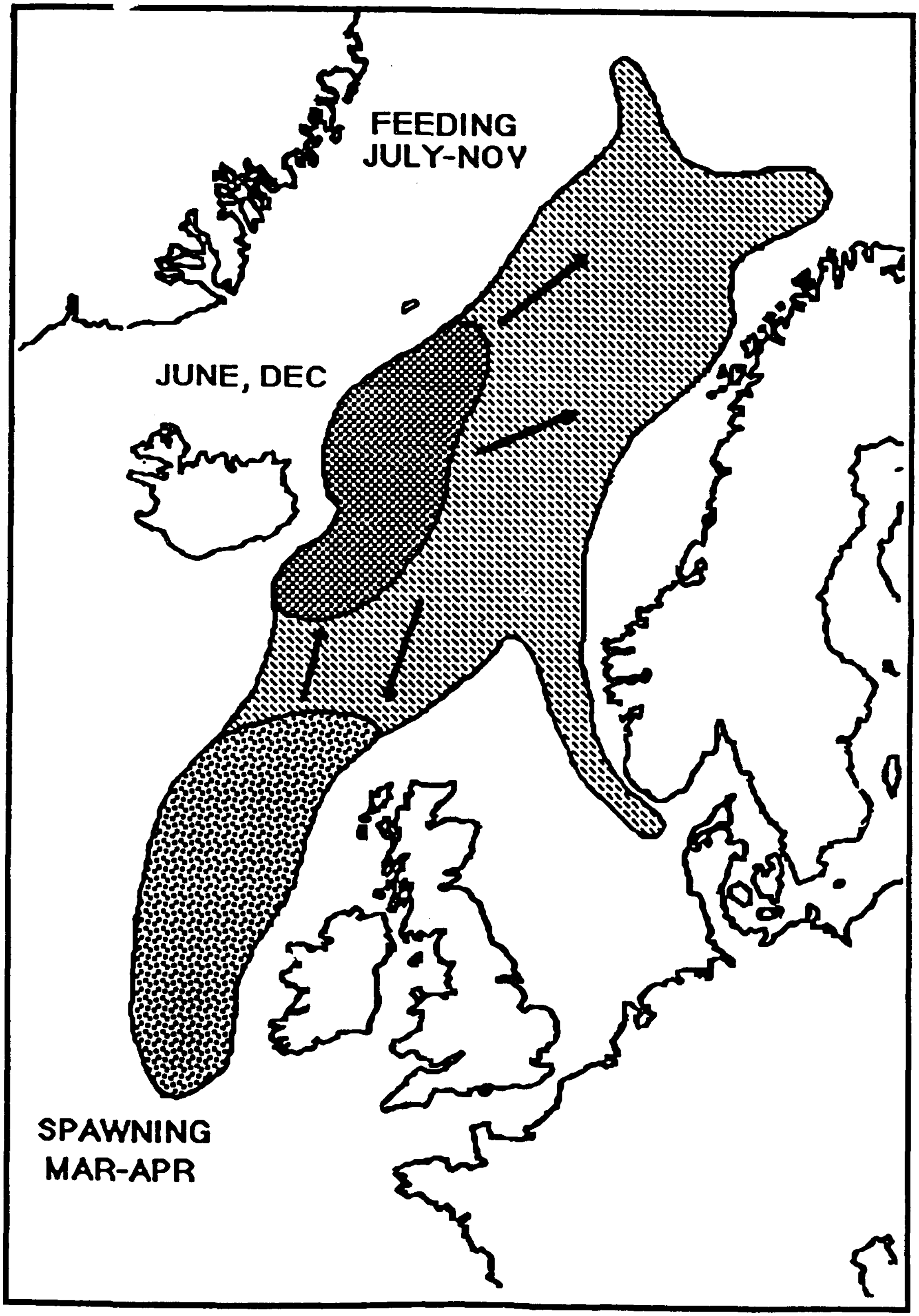


Figure 1. Migration of blue whiting in the Norwegian Sea (Love, 1990).

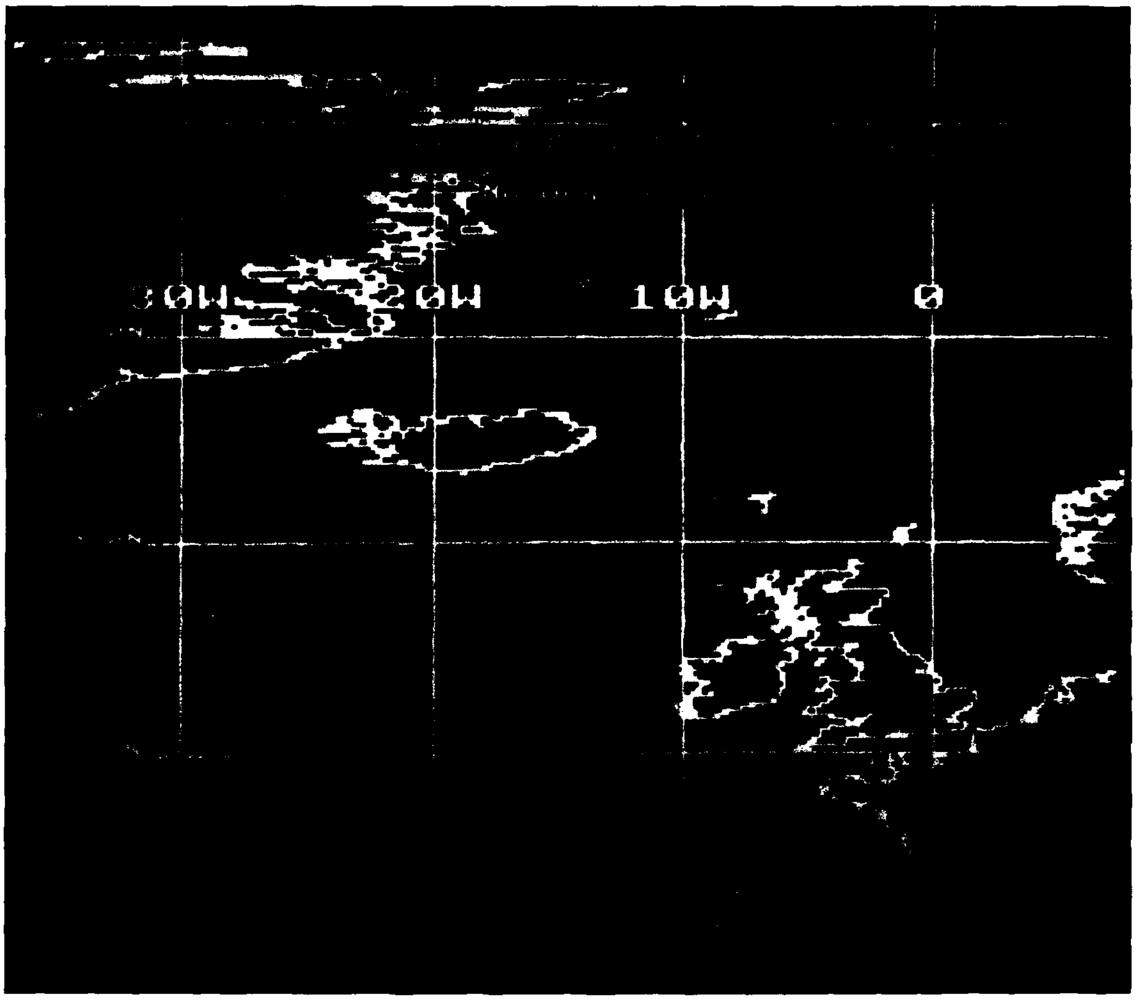
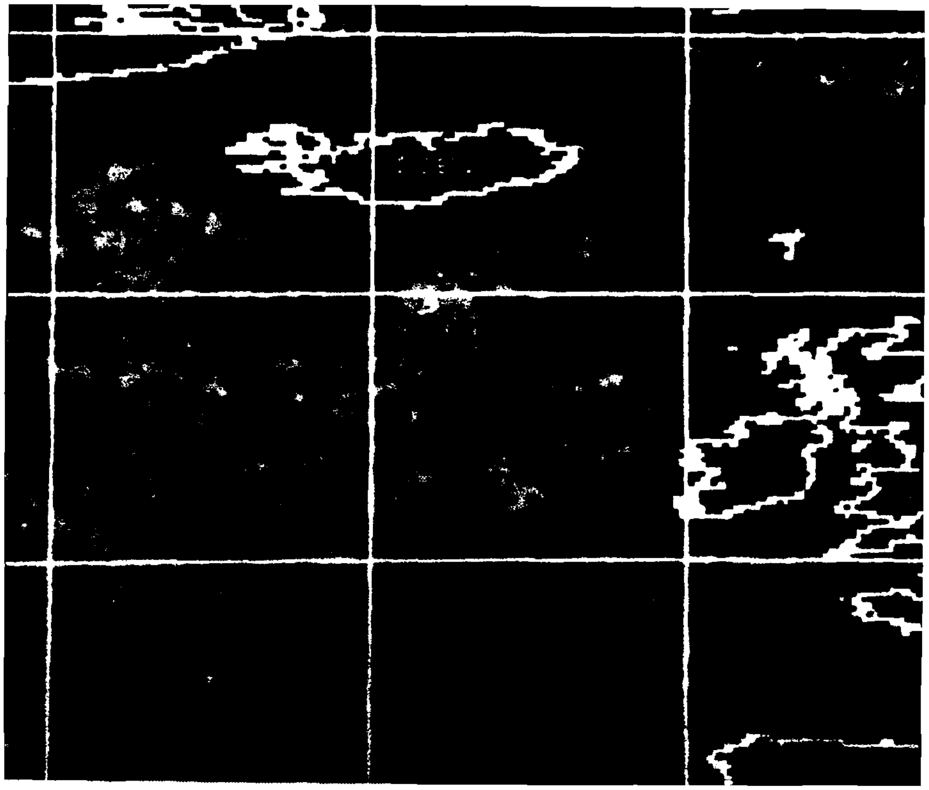
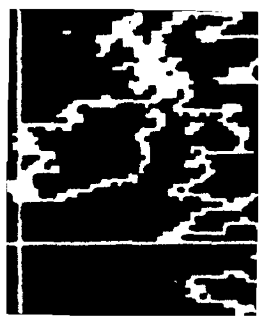


Figure 2. CZCS mean phytoplankton distribution from 1979 to 1986 for the March-April-May Spawning period.





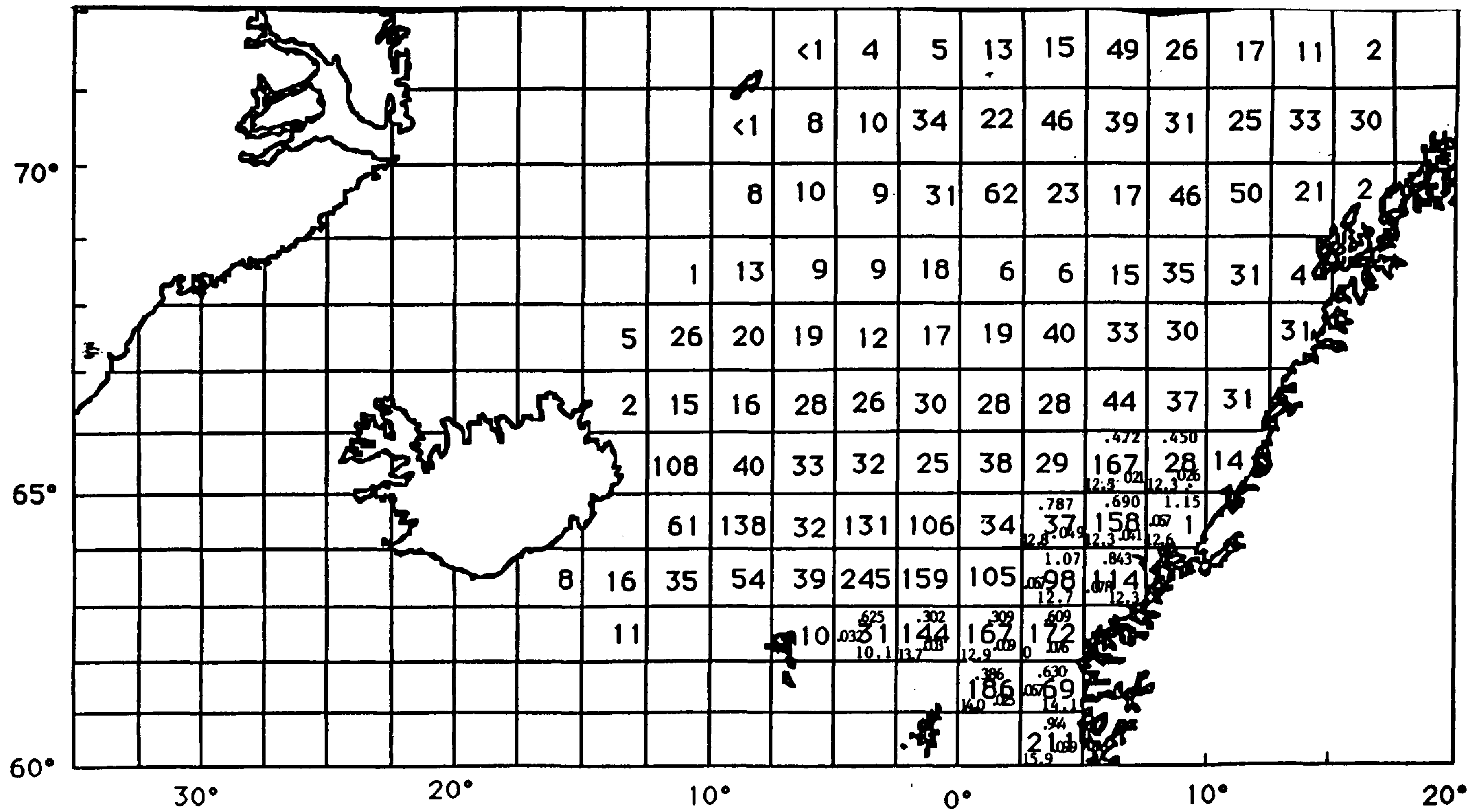
IV. Correlation of Fish Biomass and Satellite Data

The distribution and relative densities of blue whiting based on acoustic surveys conducted in August from 1982 to 1986 are illustrated in figures 5 through 8 (Anon, 1982-1986; Love, 1990). These survey data represent combined USSR, Norway, GDR, Iceland and Faroes, acoustic surveys of the biomass of blue whiting in each 2.5° of longitude and 1° of latitude (approximately 60 x 60 nmi) for the Norwegian Sea. A more complete description of the survey and implications of the migrations are presented in Love (1990).

The satellite phytoplankton and SST data bases were reviewed for coincident data points during August of 1982, '83, '84, and '85 in the Norwegian Sea. The area searched was bounded by 60.0° N and 74.0° N latitude, and 30.0° W and 20.0° E longitude. An example of the phytoplankton distribution for August 1984 is shown in figure 9. The corresponding standard deviation of the chlorophyll is shown in figure 10. The AVHRR SST image is shown in figure 11.

Using the survey biomass grid points, the coincident mean and standard deviation chlorophyll concentration, and SST were obtained for comparison and correlation. Of the total 473 biomass grid points, there were 150 coincident satellite data points (32%). The standard deviation chlorophyll distribution is an indicator of the variability occurring within the area. Variability in ocean regions partially occurs in response to ocean fronts within a region. These standard deviation distribution can be considered an estimate of the frontal positions. Local fish concentrations are commonly associated with frontal position and thus the standard deviation of the chlorophyll could be correlated with the local blue whiting distribution. Note that the standard deviation of chlorophyll is directly correlated to the mean chlorophyll, and thus, is not always associated with frontal positions.

Figure 5. Acoustic survey from August 1982 indicating the fish biomass for grid areas (Love, 1990)(large number). Within each grid the corresponding mean and standard deviation monthly phytoplankton concentration and the sea surface temperature (SST). SST in the bottom number (°C), chlorophyll (mg/m^3) on the top, chlorophyll standard deviation in the middle.



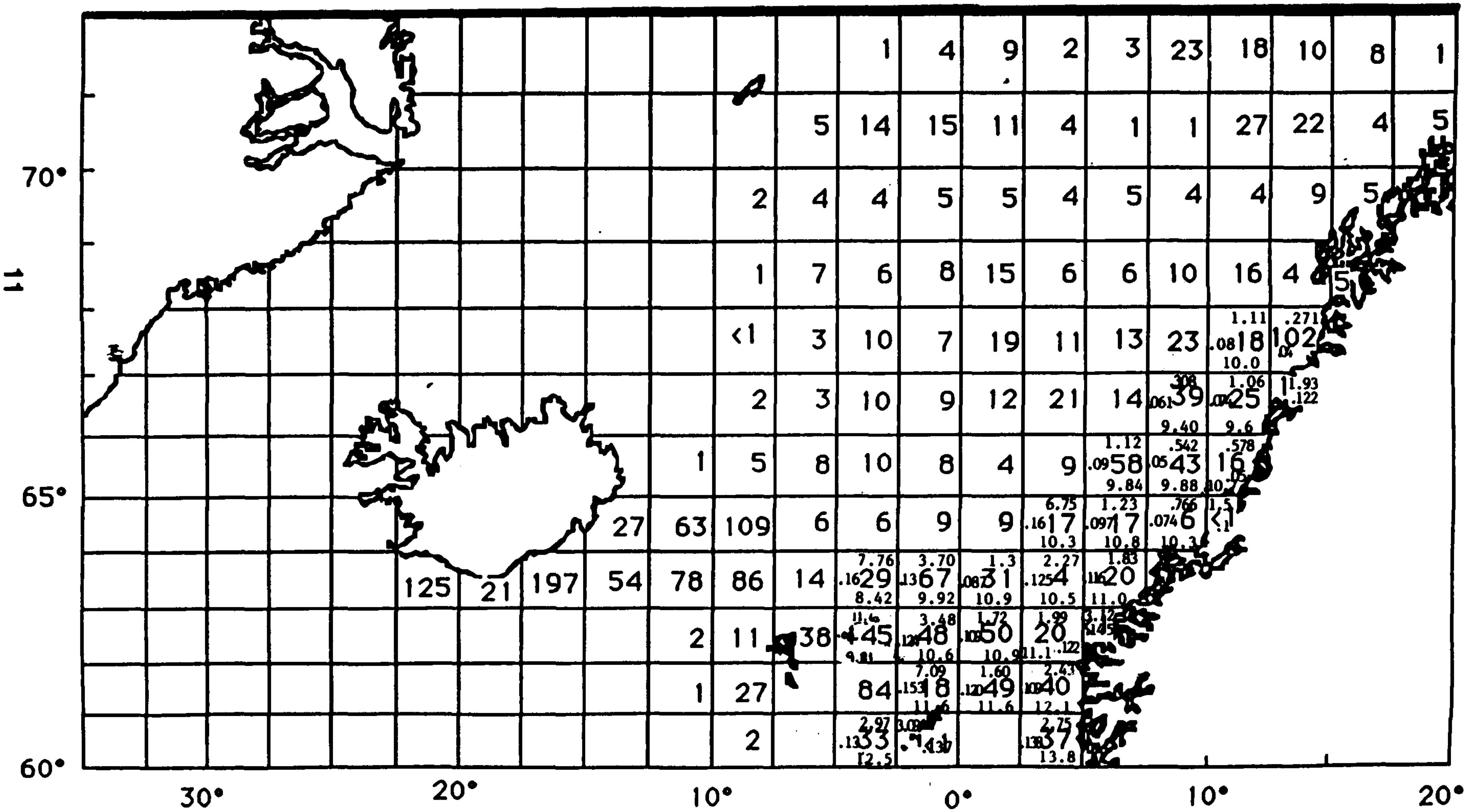


Figure 6. Acoustic survey from August 1983.

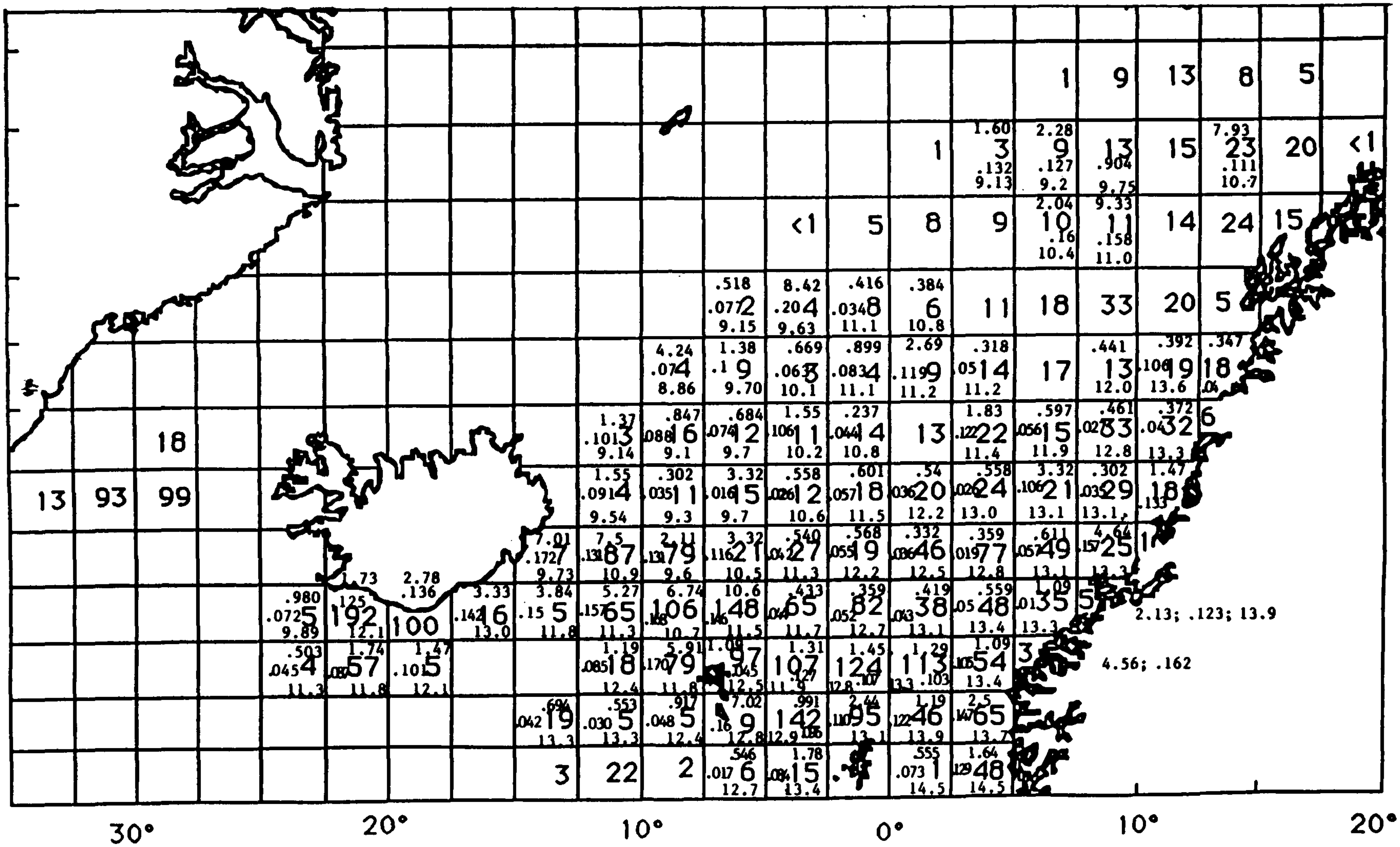


Figure 7. Acoustic survey from August 1984.

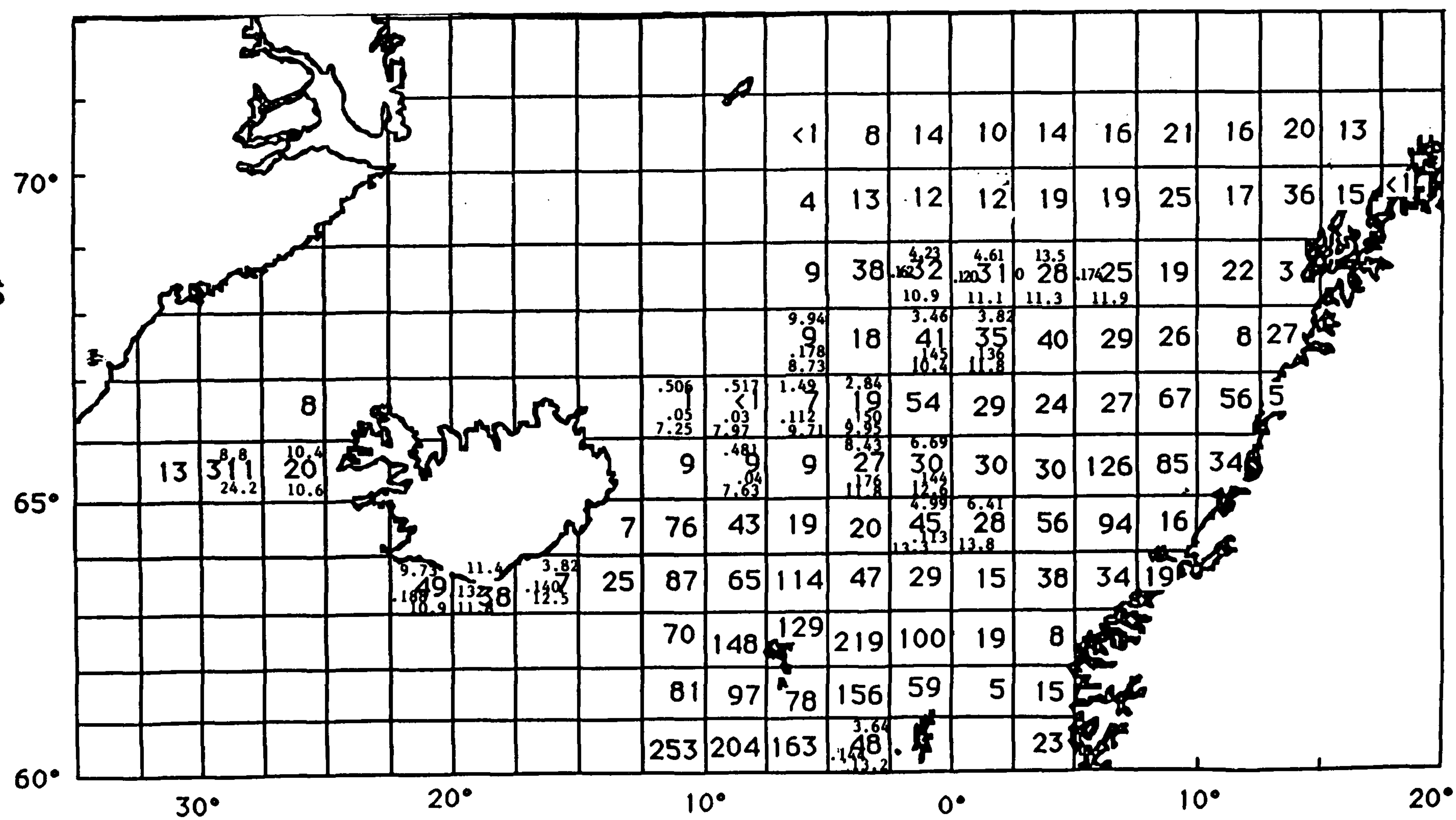


Figure 8. Acoustic survey from August 1985.

Figure 9. An example of the mean phytoplankton from August 1984 that were used in the correlation study. The pixel resolution is 20 km.

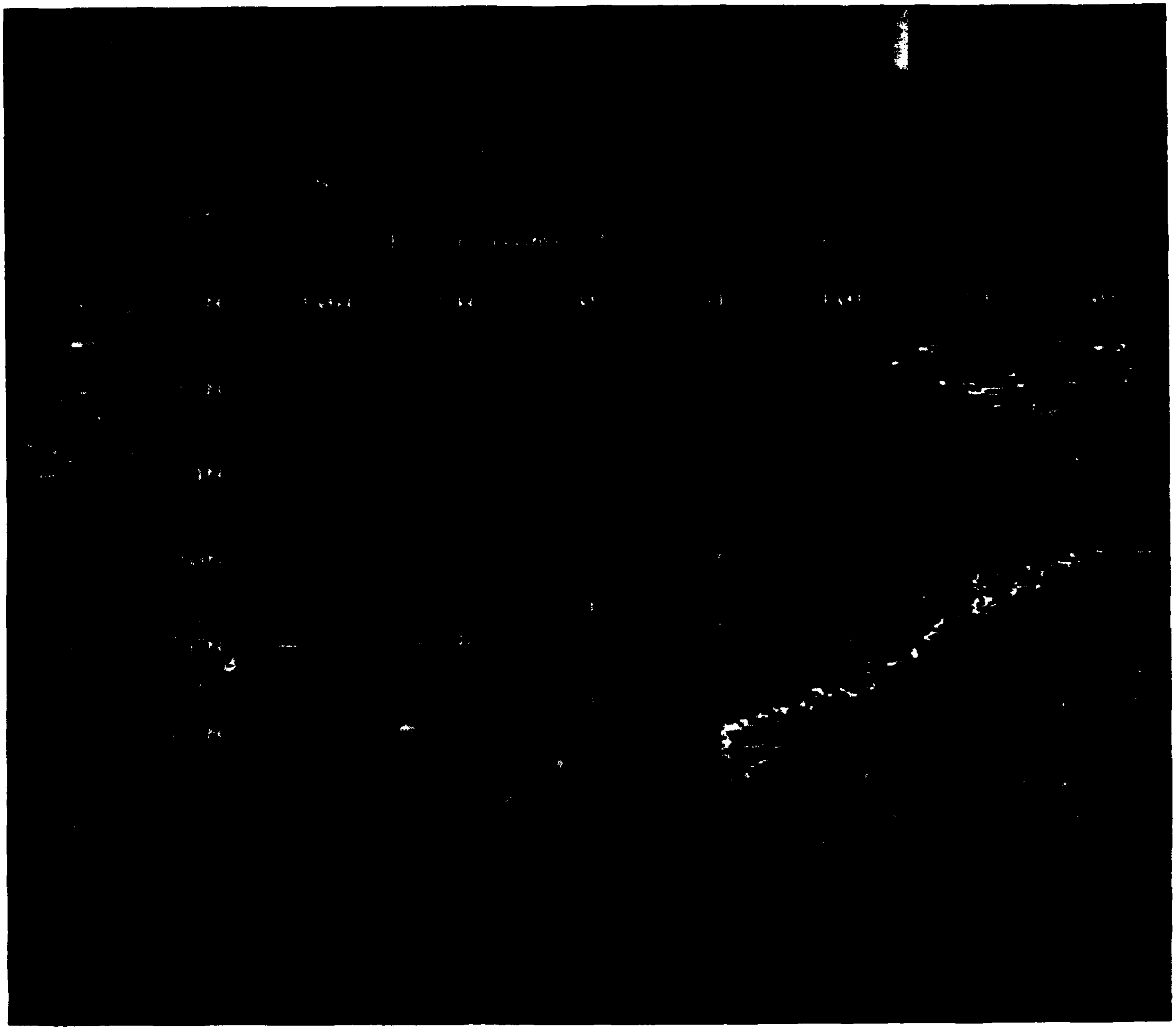


Figure 10. An example of the standard deviation of the phytoplankton distribution from August 1984 within the 20-km pixels.

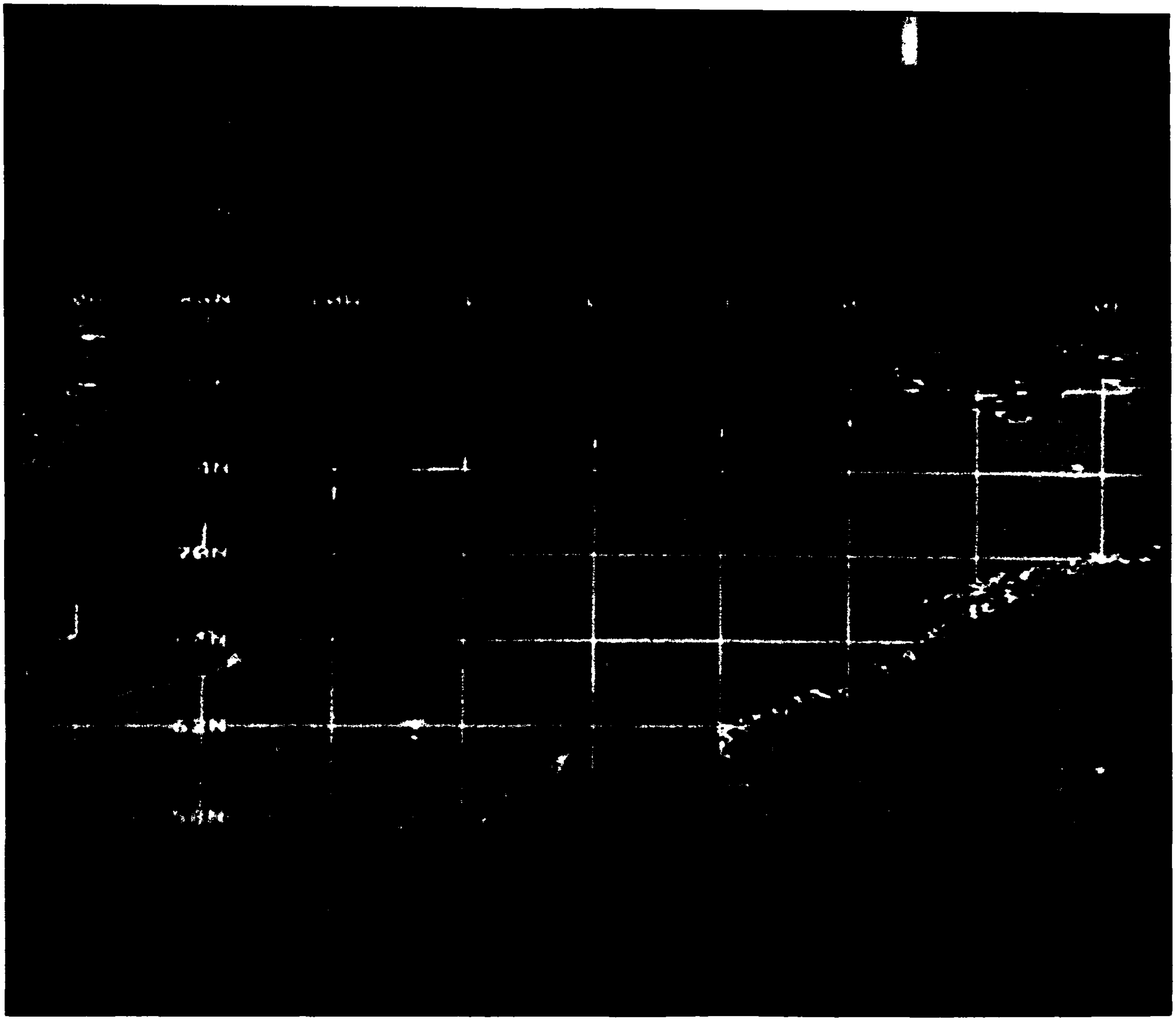
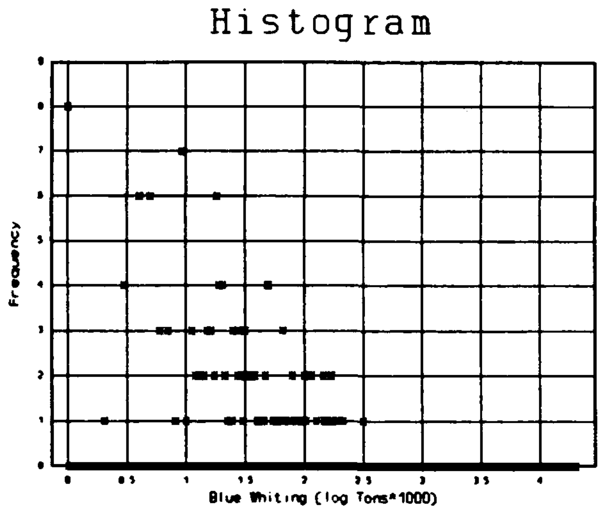


Figure 11. An example of the sea surface temperature distribution from August 1984 illustrating the monthly average.



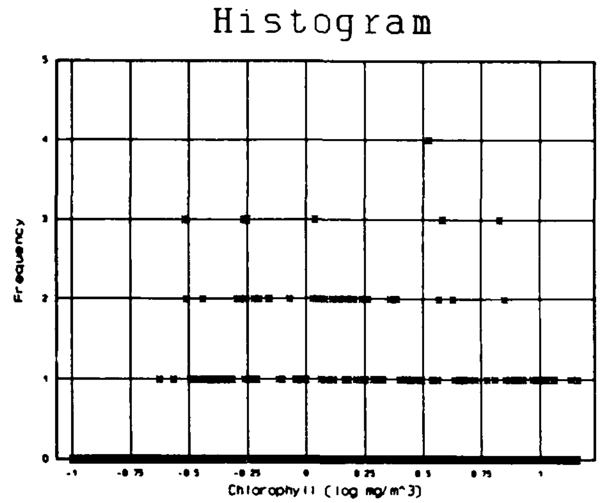


Figure 12 a. Normal distribution of the log transformed fish biomass.

Figure 12 b. Normal distribution of the log transformed chlorophyll concentration.

The biomass tonnage grid points covered an area that was approximately 60 nm latitude x 60 nm longitude. These grid points translated into a "box area" on the 20-km resolution satellite data bases of 5 pixels in latitude x 5 pixels in longitude. A 5 x 5 pixel box was centered on the same lat/long point that was the center of the biomass grid point. The average of the satellite data occurring within the box was determined for the mean and standard deviation of the chlorophyll concentration and the mean SST. These data are shown for each grid point are also shown on figure 6 through 10. The majority of the coincident data occurred south of 67.0° N and east of Iceland.

The data set of chlorophyll, standard deviation, MCSST, and biomass were analyzed using linear regression. Single and multivariable regressions were used in an attempt to predict blue whiting from the chlorophyll and SST. Chlorophyll and fish biomass were transformed using log(x) to reduce heteroscedasticity and give more symmetric distribution of the variance around the mean. The histogram of the SST was shown to be Gaussian and a transform was not required. The histogram of +(formed fish biomass and the chlorophyll are shown in figures 12 a and b. The standard deviation of the chlorophyll was not log transformed.

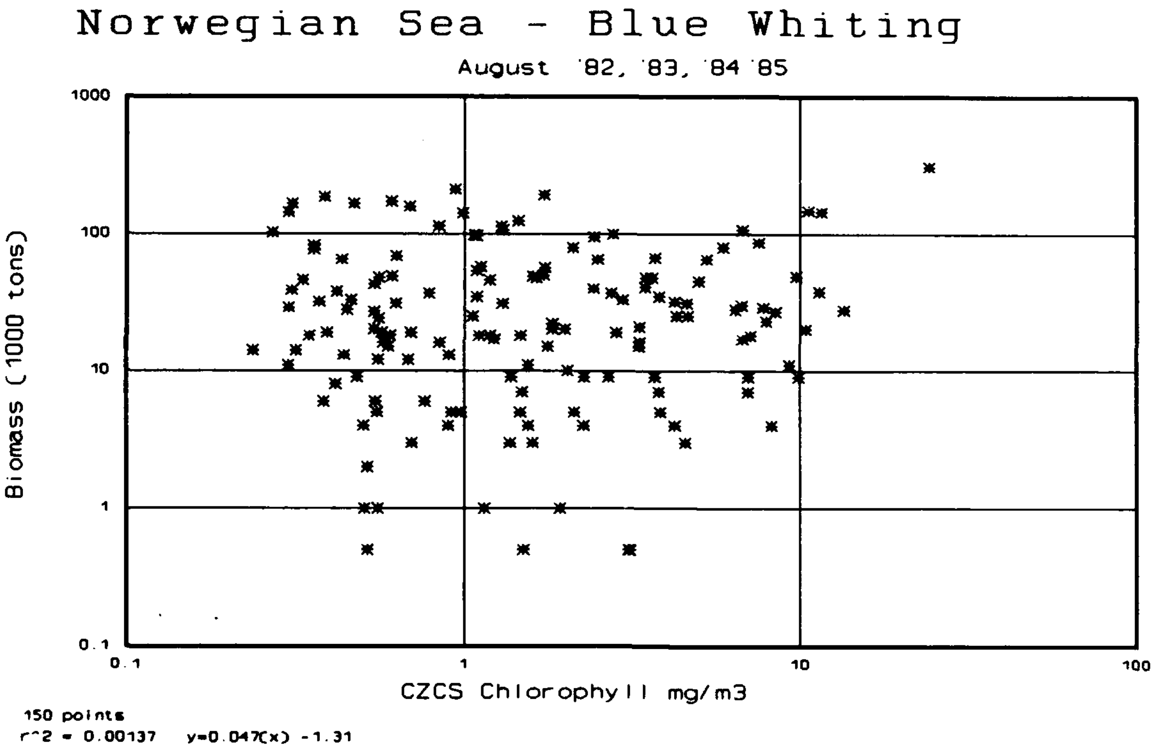


Figure 13. Scatterplot of the log transformed chlorophyll and log transformed blue whiting.

IV. Results

The results of the correlations for the different parameters are shown in table 1. The linear correlation coefficient, r^2, represents the degree of correlation between the independent and dependent data sets. The coefficient approach one with increased correlation. The X column of the table represents the independent variable and the Y column represents the dependent.

The plot of the log blue whiting biomass and log mean chlorophyll for the 150 coincident points figure 13 shows a high scatter (r^2= 0.00137, P=0.5) suggesting that chlorophyll alone cannot be used to predict biomass. (P is the probability of obtaining a r^2 given no relationship between the variables. Lower P values suggest a higher confidence in the correlation and P < 0.05 are considered significant.) These poor relationships indicate that the fish distribution is not very well explained by ocean surface phytoplankton concentrations alone, or that the surface chlorophyll is not linked to the vertical chlorophyll distribution.

The relationship of log blue whiting biomass and SST is illustrated in figure 14. Fish biomass is significantly positively correlated with SST (r^2 =0.1203, P=0.001) suggesting that at higher fish biomass occurs in regions of higher SST. The relationship:

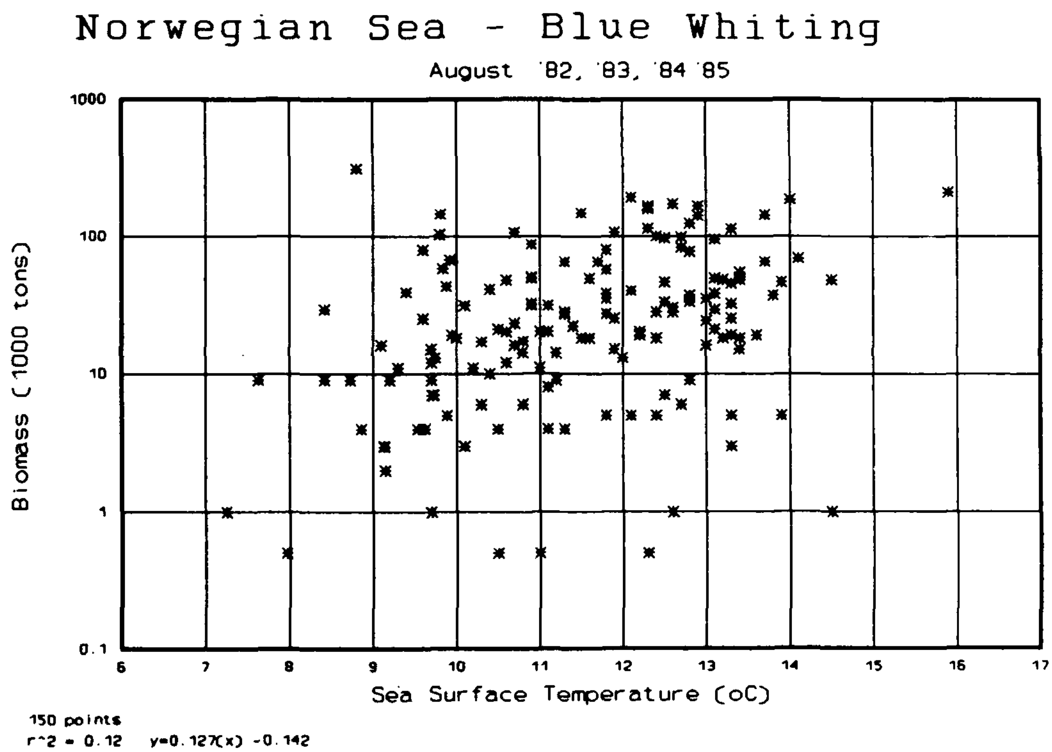


Figure 14. Correlation of the SST and the log blue whiting.

$$\text{Log Fish} = 0.127^{*}\ \text{SST} - 0.142 \qquad (1)$$

is shown in figure 14. Although there is high scatter, the relationship does span two orders of magnitude of fish density that is equivalent to a 20-Db range in volume scattering.

In addition, log chlorophyll is not well predicted by SST. Although significant (r^2= 0.028, P=0.02), the wide scatter would have little predictive utility. The poor relationships between fish biomass and surface chlorophyll indicates that the fish distribution is better explained by ocean SST than surface phytoplankton concentration.

Multiple regression analyses were performed to determine if the significant correlation between blue whiting biomass and SST could be improved by the addition of other variables. Although marginal, the best correlation (r^2 = 0.1435) was observed using log chlorophyll in combination with SST and chlorophyll standard deviation.

Log chlorophyll in combination with SST also provided a significant correlation with fish biomass with a r^2 of 0.1296.

Table 1.
Regression Analyses of Fish Biomass and Satellite Properties.

Variable - Parameter

Y	X_1	X_2	X_3	R^2	b	M^1	M^2	M^3
LBiomass	LChl	SST		0.1296	-0.235	0.1237	0.133	
LBiomass	SST			0.1203	-0.142	0.127		
LBiomass	LChl			0.0013	-1.311	0.0469		
LCHL	SST			0.0280	0.736	0.0485		
LBiomass	STD			0.0010	1.3576	-0.399		
LBiomass	SST	STD		0.121	-0.165	0.1640	0.128	
LBiomass	LChl	SST	STD	0.1435	-0.030	0.344	0.134	-2.61
LBiomass	STD	LCHL		0.0139	1.5128	0.2561	-2.49	

L = Log Chl = Chlorophyll Std = CHL Standard Deviation
SST = Sea Surface Temperature
b = y intercept M^1 = slope

IV. Conclusions

The correlation of blue whiting and SST provides a limited predictive ability for estimating the distribution of blue whiting. The addition of surface chlorophyll adds little to this relationship and suggests that the vertical chlorophyll profile is required. The limited correlation illustrated in this study suggests that our scales of resolution (spatial and temporal) are inadequate for properly correlating the fish biomass and simple satellite derived parameters. Shorter time scales than the 1-month averages are required to address the rapid response of fish behavior to evolving physical and biological processes. Fish respond to external environmental forcing both local and long term. The data-base used in this study represents average monthly conditions occurring only at the ocean surface. Although these data were synoptic for the month of August with the acoustic survey, they are **average** conditions within the 5 x 5 pixel (100 x 100 km) area. As such they do not represent the **local** environmental conditions. The local oceanographic forcing identifies features such as frontal positions (within 1 km), rings and eddies, wind events, cloudy overcast days, etc. Because of fish migration, the higher resolution satellite imagery showing detailed features may exhibit higher correlations with the fish distribution. Previous studies have identified enhanced fish densities at fronts observed from satellites. An improved correlation would be expected if satellite ocean color and thermal IR were coincident with the day of the ship survey.

At a 1-km resolution, the satellite imagery would offer an improved resolution, and hence, a better understanding of influence of local environmental conditions on the fish distribution.

The crude predictive model of fish biomass based on SST in equation (1) does provide a simple algorithm by which a rough estimate of fish biomass and approximate volume reverberation could be derived for this region of the Norwegian Sea. The significant correlation of fish biomass with SST likely occurred because a large proportion of the fish population aggregates along the warmer waters along the Iceland-Faroes front within the southern portion of the Norwegian Sea. Although high chlorophyll values were evident within the region of this front, they likely did not provide a significant correlation because within the available data, chlorophyll appears to be more spatially variable than temperature. Therefore, the correlation with temperature rather than chlorophyll may represent spatial aliasing of the data rather than an actual better predictive ability of temperature over that of chlorophyll.

The limitations of remote sensing of the sea surface can possibly account for the poor correlations. The vertical distribution of phytoplankton and temperature can be substantially different than what is observed at the surface. Fish populations should be controlled by the vertical distributions of these properties. Presently models are being constructed to define theoretical profile of chlorophyll base on surface values. Improved correlations of phytoplankton and blue whiting are expected when these vertical models are complete since blue whiting are not at the surface.

The Norwegian Sea represents an area masked by large amounts of clouds. Thus, limited cloud free imagery was available for this region. However, cloud-free imagery was found for April 7 and April 15, 1986. These images were processed (atmospheric correction) to derive chlorophyll concentration at a 1-km spatial scale. These data are shown in figures 15 and 16, and clearly show the high concentrations of chlorophyll associated with the Norwegian coastal current. Unfortunately these data do not coincide with any acoustic survey of fish. These data do show the exceptionally high chlorophyll concentration off the Norwegian coast (values in excess of 20 mg/m^3) demonstrating high local concentrations of chlorophyll. The distributions of fish population are expected to coincide with some combination of the chlorophyll and temperature fronts as displayed in this high resolution imagery. Extensive averaging of data will eliminate the high resolution spatial and temporal ocean phenomena that are likely important in predicting the fish distribution.

Predicting the distributions of fish may require oceanographic parameters in addition to phytoplankton concentration and SST. Physical ocean properties such as the vertical temperature distribution and mixed-layer depth are known to control on fish behavior. The composite average of these properties can be obtained for certain regions and should be entered into the correlation. Similarly, local solar irradiance and wind events are also available from climatological studies (Arnone and La Violette, 1991; Terrie et al., 1991). Coupling ocean climatological data bases such as phytoplankton, solar irradiance, winds, mixed-layer depth, etc., and fish distribution would enable physical and

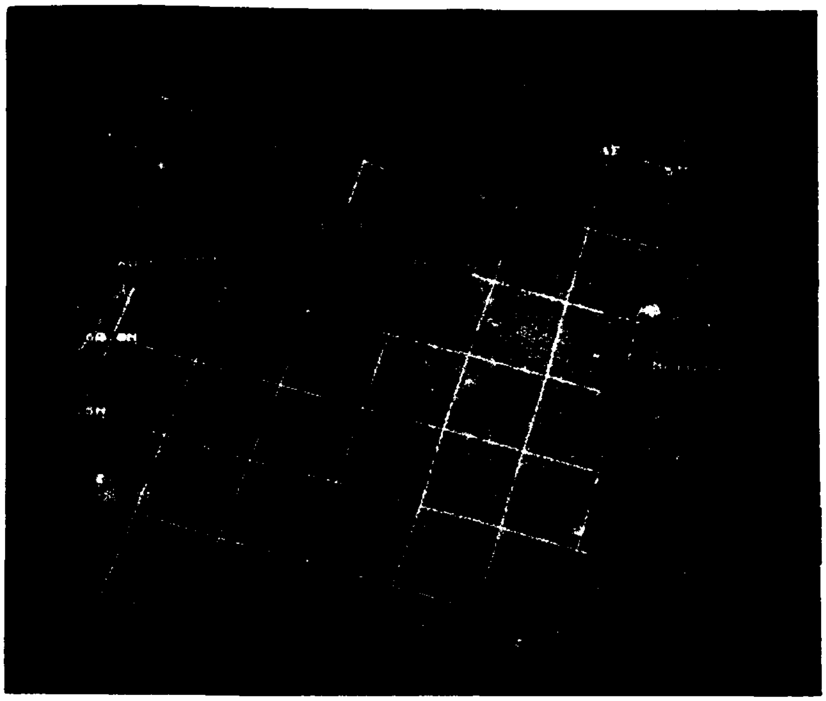


Figure 15. A 1-km resolution chlorophyll image for April 7, 1986 is shown. The Norwegian coastal current is clearly shown as elevated chlorophyll.

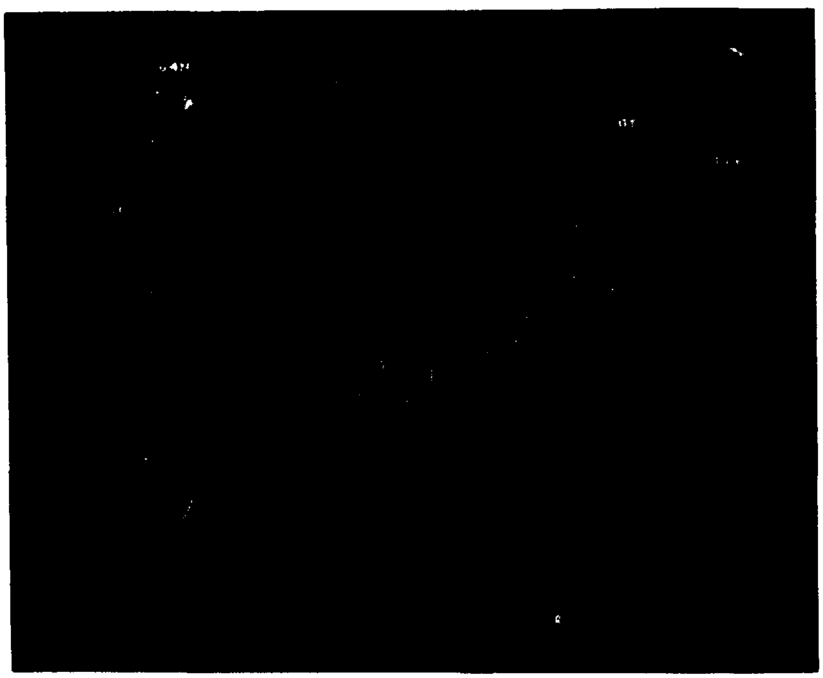


Figure 16. A 1-km resolution chlorophyll image for April 15,1986 shows the exceptionally high chlorophyll bloom occurring along the Norwegian coast.

biological processes to be associated with fish behavior. This integrated approach would permit evaluation and assessment of regional ocean basins for acoustic volume reverberation. Combining this assessment with "real time" satellite surveillance from ocean color and SST data could provide validation and improvements to predicting the acoustic volume reverberation.

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